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CENTRALIZED DISCRETE STATE SPACE MODEL PREDICTIVE CONTROL AND DECENTRALIZED PI-D CONTROLLER OF AN AEROTHERMIC PROCESS

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***Abstract-** The aerothermic process is a pilot scale heating and ventilation system equipped with a heater grid and a centrifugal blower. The interaction between its main variables is considered as challenging for mono-variable controllers. A change in the ventilator speed affects the temperature behavior which represents a factor that must be managed for energy saving and the human welfare. This paper presents an experimental comparison between a Centralized Discrete State Space Model Predictive Control (CDSSMPC) and a Decentralized PI-D (DPI-D) controller. These both techniques are designed by using respectively the Laguerres functions and the static decoupler approach. To demonstrate the effectiveness of the two methods, an implementation on an aerothermic process is performed. This pilot scale is fully connected through the Humusoft MF624 data acquisition system for real time control. The results show satisfactory performance in closed-loop of the DPI-D controller compared to the CDSSMPC and the conventional PID ones.*

Index terms: Centralized discrete state space model predictive control, Laguerre functions, Static decoupler, Decentralized PI-D controller, Multivariable systems, Aerothermic process.

I. INTRODUCTION

The heating and ventilation play an important role in human thermal comfort especially for the people, which perform their activities within the building offices. It is also the case in many industrial sectors including chemical, mineral, drying and distillation processes, as well as pharmaceutical and agro alimentary production units where the temperature is a critical parameter. Thus, an important factor is to look for a tradeoff between the energy conservation and the person's welfare in order to maintain the healthy and safe working environment to the conditioned space. Although the temperature control is no more a challenging control problem in most of these applications. Nevertheless, some practical issues in many temperature control applications stimulate new developments and further investigations [1-14].

For education and searching purposes, many types of aerothermic processes are available. They highlight most heating and ventilation problems, and they are widely referenced in the process control literature. Different prototypes of these processes have been used to check new control strategies and many results were reported in the single variable control cases [1-2,8,11,14].

The aerothermic processes are generally subject to significant interactions between its main variables. However, they were not explicitly considered in most reported control. Worth to mention herein that the basic factory control system delivered with most of aerothermic processes is restricted to the classical analog PID controller without taking into account of interactions between its main parameters [15].

In this paper, the Decentralized PI-D controller (DPI-D) [1] is considered and compared to both a Centralized Discrete State Space Model Predictive Control (CDSSMPC) [4] and a conventional PID controller to ensure the desired level of temperature and air flow of the aerothermic process. To fulfil the requirement for integral action in the CDSSMPC controller, it is embedded with integrators to achieve this objective and ensure outputs steady-state error free [16]. The implementation of the discrete state space predictive control in real time is based on the result of the cost function minimization and only the first input of the optimal command sequence is used each time a new state is updated. In the synthesis of the CDSSMPC and the DPI-D controllers, a multivariable model is identified using a numeric direct continuous-time identification approach [1-2,17-20].

The paper is organised as follows. Section II introduces the description of the aerothermic process and underlines the interaction between the main process variables. Section III discusses the multivariable direct continuous-time identification of the aerothermic process, which is represents the first step in the design of both the DPI-D and the CDSSMPC controllers. Section IV introduces the CDSSMPC algorithm where integral actions and set-point tracking are naturally embedded in the algorithm. In this section, we recall the main steps in the development of quadratic programming which implement the CDSSMPC and the Laguerre functions. Also, this section describes the proposed DPI-D controller based on the static decoupler [1]. Its parameters are calculated by using the IMC tuning rules. Section V reports the experimental control results of the aerothermic process operation. Robustness of the DPI-D controller compared to the CDSSMPC ones is also discussed and a final conclusion is given.

II. AEROTHERMIC PROCESS DESCRIPTION

The considered pilot scale aerothermic process [1-3,15], is shown as a schematic diagram in figure 1 and depicted in a three dimensional view in figure 2. It has the basic characteristics of a large process, with a tube through which atmospheric air is drawn by a centrifugal blower, and is heated as it passes over a heater grid before being released into the atmosphere.

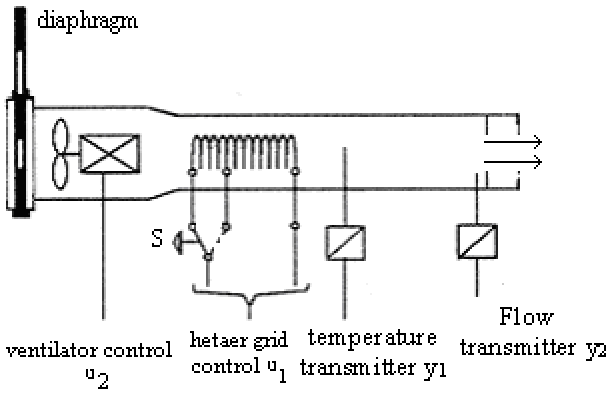

Figure 1. Schematic illustration of aerothermic process

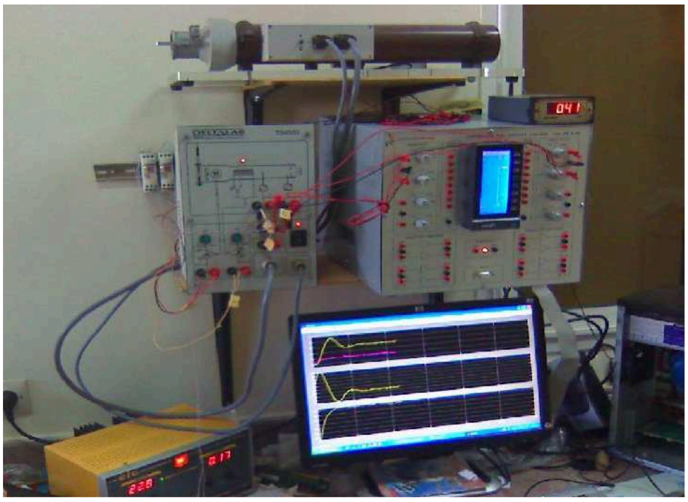

Figure 2. Three-dimensional view of aerothermic process and analog PID

The temperature control is achieved by varying the electrical power supplied to the heater grid. There is an energized electric resistance inside the tube, and due to the Joule effect, heat is released by the resistance and transmitted, by convection, to the circulating air, resulting in heated air [13]. The air flow is adjusted by varying the speed of the ventilator.

This process can be characterized as a non-linear system. The physical principle which governs the behaviour of the aerothermic process is the balance of heat energy. Hence, when the air temperature and the air flow inside the process are assumed to be uniform, a linear system model can be obtained. This kind of aerothermic process is being used by many researchers to check their new control strategies [1-4,6,14].

As shown in the schematic of the aerothermic process, the system inputs, (u_1, u_2), are respectively the power electronic circuit feeding the heating resistance and the ventilator speed. The outputs, (y_1, y_2), are respectively the temperature and the air flow. The input-output signals are expressed by a voltage, between *0* and *10* V, issued from the transducers and conditioning electronics.

To examine the possibility of interaction between the temperature and air flow, two experiments were carried out. In each case, the two process inputs were held constant and allowed to settle. If one of them undergoes a step change, the behaviour of the other output will be observed to see if this change had any effect on it. Figure 3 shows the results from both experiments.

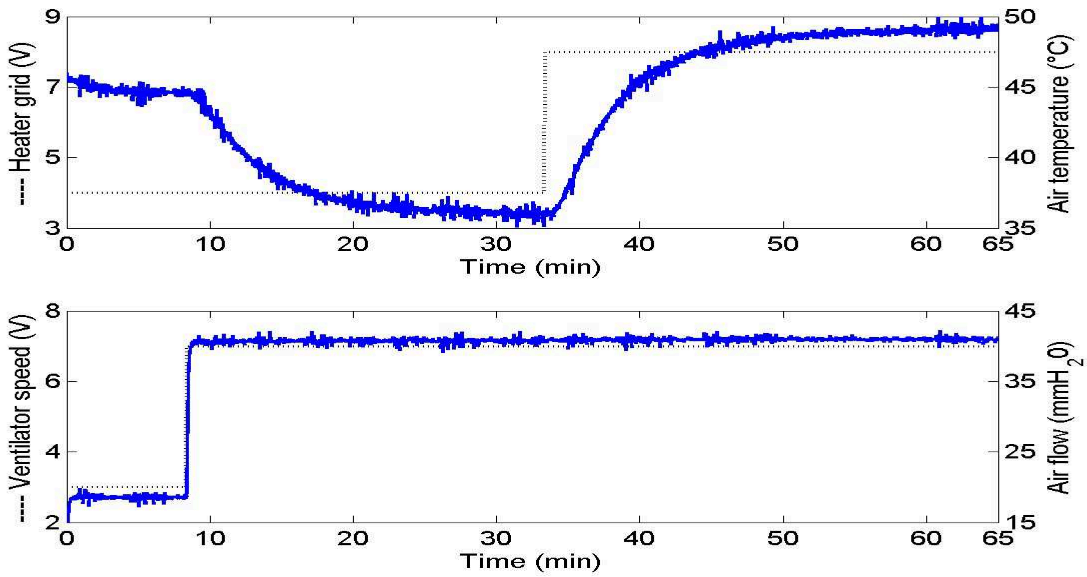

Figure 3. Interactions between the main variables of the aerothermic process

In the first half plot of this figure, the electric voltage supplied to the heater grid is held constant (at *4V*) and the ventilator speed undergoes a step change from *30%* to *70%* of its full range. The air temperature varied considerably from *4V* (*45°C*) to *2V* (*35°C*). The second half plot shows the results when the ventilator speed is held constant and the electric voltage of the heater grid undergoes a step change, from *40%* to *80%* of full range. As can be seen, the air temperature is varied accordingly but the air flow is remained unaffected.

These results show that the air temperature behaviour depends also of the operating conditions of the air flow. Hence, the change in air temperature behaviour is provided by two effects: a direct effect, by the heater grid and indirect effect via the ventilator speed. Our main aim is then to eliminate the indirect effect.

The main objectives to applying the Centralized DSSMPC and the Decentralized P-ID controller are to searching for desired levels of the temperature and the air flow by reducing completely or partially the interactions effect.

III. MATHEMATICAL MODELS

The system identification is an experimental approach to determine the transfer function or equivalent mathematical description for the dynamic of an industrial process component by using a suitable input signal. This approach represents the first step in the design of a most controller.

In order to generate estimation and validation data for system identification, an experiment is performed. Data set used for the parameter identification step is build up with Pseudo Random Binary Sequence (PRBS) signals which are applied simultaneously to the two manipulated variables of aerothermic process. This data set and their correspondent outputs are displayed in figure 4. The sampling interval is T_s=1 second. The signals collected, via the Humusoft MF624 data acquisition module, are yield in the interval (0V, 10V).

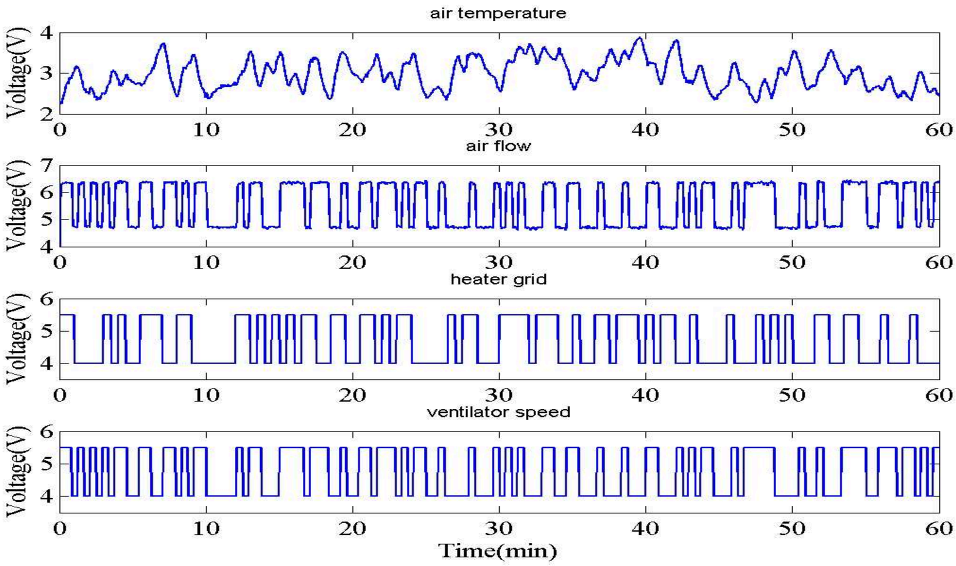

Figure 4: Data set for direct continuous-time identification

After the application of the DCTI approach on first half experimental sampled data of identification (i.e.: 30 minutes), the identified models of the aerothermic process suggests that the dynamic relationship between the measured inputs and the measured outputs, for the two loops, are linear and first-order plus dead time (FOPDT). Its transfer function is given by the following equation:

$$G(s) = \frac{Ke^{-\theta s}}{\tau s + 1} \qquad (1)$$

where K represents the steady-state gain, τ is the time constant, and θ is the time delay of the system.

The identified multivariable transfer functions of the aerothermic process are given by the following system equation [1-2]:

$$\begin{pmatrix} Y_1(s) \\ Y_2(s) \end{pmatrix} = \begin{pmatrix} \dfrac{0.7891}{34.0716s+1}e^{-7s} & \dfrac{-0.4616}{30.9789s+1}e^{-7s} \\ 0 & \dfrac{1.0888}{1.4302s+1}e^{-s} \end{pmatrix} \begin{pmatrix} U_1(s) \\ U_2(s) \end{pmatrix} \tag{2}$$

This equation can be shown as a schematic diagram in figure 5

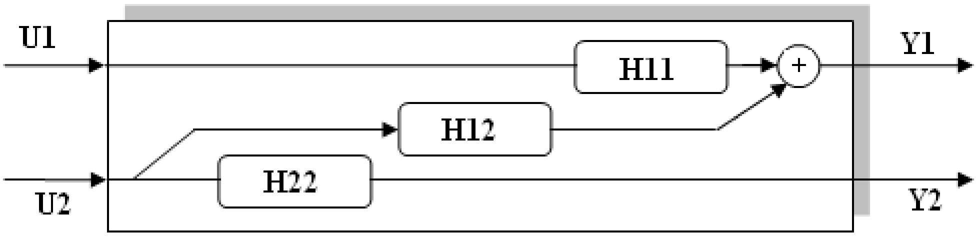

Figure 5: Schematic illustration of a partial interaction

where

$$H_{11}(s) = \frac{0.7891}{34.0716s+1}e^{-7s}$$

$$H_{22}(s) = \frac{1.0888}{1.4302s+1}e^{-s}$$

$$H_{12}(s) = \frac{-0.4616}{30.9789s+1}e^{-7s}$$

represent respectively the continuous process transfer functions of first loop, the continuous process transfer functions of the second loop and the continuous transfer function of the process interaction.

The negative gain in the interactive transfer function, $H_{12}(s)$, implies that the air temperature behaves in the opposite way. In fact, the interaction effect tends to reduce the air temperature when the air flow increases.

To evaluate the quality of the estimated transfer function models, a cross-validation procedure has been applied to the remaining experimental data were not used to build the model. Cross-validation result is plotted in Figures 6. From this figure, it may be observed that there is a relatively good agreement between the measured and the simulated model output. The identified model has been validated using the remaining experimental data which were not used to build it.

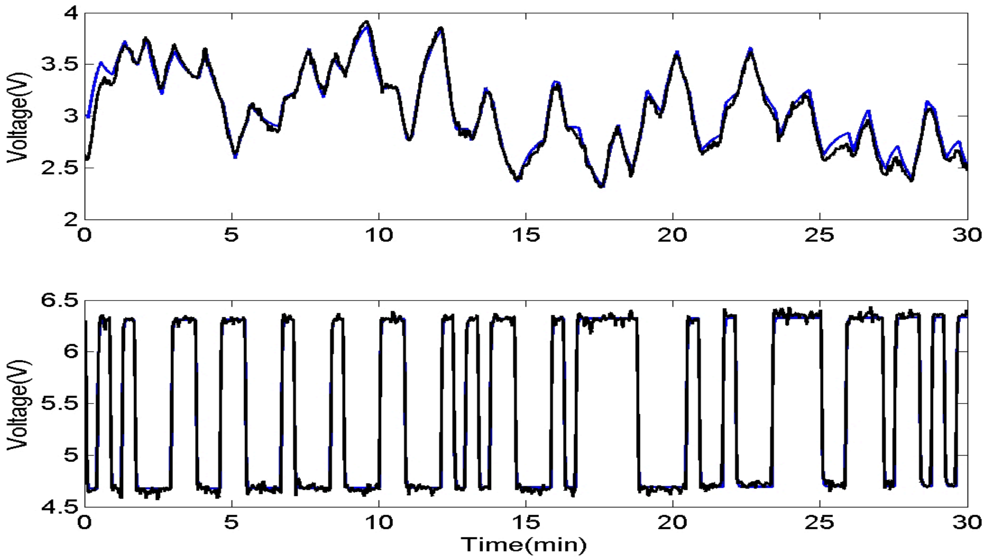

Figure 6: Cross-validation results (black: measured output; blue: simulated output)

Subsequently, the continuous-time transfer function model (2) is converted to a discrete time state-space model which will be used, in the next section, as the basis for the state space model predictive controller. The discrete time state space model, describing the aerothermic process, is given by the following equation:

$$\begin{cases} x_m(k+1) = A_m x_m(k) + B_m u(k) \\ y(k) = C_m x_m(k) \end{cases} \tag{3}$$

where

$$A_m = \begin{pmatrix} 1.0110 & -0.1180 & 0.0338 & 0 & 0 \\ 0.0701 & 0.7624 & 0.0581 & 0 & 0 \\ -0.0614 & 0.1801 & 0.9174 & 0 & 0 \\ 0 & 0 & 0 & -0.0591 & -0.3888 \\ 0 & 0 & 0 & 0.2780 & 0.6914 \end{pmatrix},$$

$$B_m = \begin{pmatrix} 0.1019 & 0.0303 \\ -0.1310 & 0.1600 \\ 0.1146 & 0.0753 \\ 0 & 0.5560 \\ 0 & 0.4414 \end{pmatrix},$$

$$C_m = \begin{pmatrix} 0.0824 & 0.1013 & -0.1046 & 0 & 0 \\ 0 & 0 & 0 & -0.3806 & 0.7613 \end{pmatrix}$$

The matrix D_m is equal to zero, $u = [u_1, u_2]^T$ and $y = [y_1, y_2]^T$. The system described by these matrices is stable, completely observable and controllable.

IV. CONTROL PROBLEM

IV-1 STATE SPACE MODEL PREDICTIVE CONTROLLER

The centralized discrete state space model predictive control used in the control of the aerothermic process is designed using Laguerre function functions [16]. As in most industrial control, to ensure outputs steady-state error free, it is embedded with two integrators. Then, the augmented aerothermic process model is introduced as:

$$\begin{cases} \underbrace{\begin{bmatrix} \Delta x_m(k+1) \\ y(k+1) \end{bmatrix}}_{x(k+1)} = \underbrace{\begin{bmatrix} A_m & 0_p \\ C_m A_m & I_{nxn} \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} \Delta x_m(k) \\ y(k) \end{bmatrix}}_{x(k)} + \underbrace{\begin{bmatrix} B_m \\ C_m B_m \end{bmatrix}}_{B} \Delta u(k) \\ y(k) = \underbrace{\begin{bmatrix} 0_{nxl} & I_{nxn} \end{bmatrix}}_{C} \underbrace{\begin{bmatrix} \Delta x_m(k) \\ y(k) \end{bmatrix}}_{x(k)} \end{cases} \tag{4}$$

where

$m=2$, $n=2$ and $l=5$. I is the unit matrix,

$$\Delta x_m(k+1) = x_m(k) - x_m(k-1)$$
$$\text{and } \Delta u(k+1) = u(k) - u(k-1)$$

For notational simplicity, equation (4) is given by the following equation:

$$\begin{cases} x(k+1) = Ax(k) + B\Delta u(k) \\ y(k) = Cx(k) \end{cases} \tag{5}$$

where x, A, B and C are respectively the state vector and matrices corresponding to the forms given in the equation (4).

The objective of the CDSSMPC controller is to find the optimal control which minimizes the following cost function [16]:

$$J = \sum_{i=1}^{N_p} x(k)^T Qx(k) + \eta^T R\eta \tag{6}$$

where $Q\geq 0$ and $R>0$ are symmetric positive definite matrices.

The optimal solution of the equation (6) is given by the following equation [16]:

$$\eta = -\left(\sum_{m=1}^{N_p} \Phi(m)Q\Phi(m)^T + R \right)^{-1} \left(\sum_{m=1}^{N_p} \Phi(m)QA^m \right) x(k) \tag{7}$$

For simplicity of the expression, the vector η is expressed as:

$$\eta = -\Omega^{-1}\Psi x(k) \tag{8}$$

where

$$\Omega = \sum_{m=1}^{N_p} \Phi(m)Q\Phi(m)^T + R$$

$$\Psi = \sum_{m=1}^{N_p} \Phi(m)QA^m$$

$$\Phi(m) = \left(\sum_{i=0}^{m-1} A^{m-i-1}BL(i)^T \right)^T$$

The $L(i)^T$ is the transposed Laguarre function vector.

After obtaining the optimal coefficient vector η, the receding horizon control law is realized as

$$\Delta u(k) = \begin{bmatrix} L_1(0)^T & 0_2^T \\ 0_1^T & L_2(0)^T \end{bmatrix} \eta \tag{9}$$

where $L(0)^T = \left[l_1(0) \quad l_2(0) \quad \dots \quad l_N(0) \right]$

and for a given N and a,

$$l_i(0) = \sqrt{1-a^2}\left[1 \quad -a \quad a^2 \quad -a^3 \quad \dots \quad (-1)^{i-1}a^{i-1} \right]$$

Since in the case of the aerothermic process the state variable $x(k)$ is not measurable (i.e.: C is different to the identity matrix), the linear discrete time observer is used to estimate it from available output. The control law is then computed using the estimated state variables given by the following equation:

$$\hat{x}(k+1) = A\hat{x}(k) + B\Delta u(k) + K_{obs}(y(k) - C\hat{x}(k)) \quad (10)$$

where K_{obs} is the Kalman filter gain Obtained by solving recursively (for i = 0, 1, . . .) the following equation:

$$\begin{aligned} &K_{obs}(i) = AP(i)C^T(\alpha + CP(i)C^T)^{-1} \\ &P(i+1) = Ap(i)A^T - AP(i)C^T \\ &(\alpha + CP(i)C^T)^{-1} CP(i)A^T + \beta \end{aligned} \quad (11)$$

α and β are the matrices to be chosen by the user.

IV-2 DECENTRALIZED PI-D CONTROLLER

In the multi-variable processes where the interactions usually exist among the loops, a sudden change in the set-point of one loop will be a large load disturbance to the other loops. Hence, when these processes are controlled by the conventional PID controller without taking into account of these interactions, the derivative term can become very large and thus provide a "derivative kick" on the variable control [1]. In the aerothermic process case, an abrupt change in the air flow affects considerably the air temperature behaviour. Therefore, the interaction caused by the second loop needs to be eliminated. To do it, the aerothermic process must be decoupled into separate loops.

Generally, there exist two decoupling approaches: the complete decoupling and the partial decoupling. In the complete decoupling, all decouplers are used. While in the partial decoupling; only some decouplers are used and the remainder decouplers are set equal to zero. Among the advantageous of the partial decoupling, we note its tendency to be less sensitive to modelling errors compared to the complete decoupling [22]. The partial decoupling is an attractive approach for control problems where one of the controlled variables is more important than the other or where one of the process interactions is absent. In the aerothermic process case, the partial decoupling is considered in order to eliminate the interactions caused by the second loop on the first one. This partial decoupling is represented by the Figure 7.

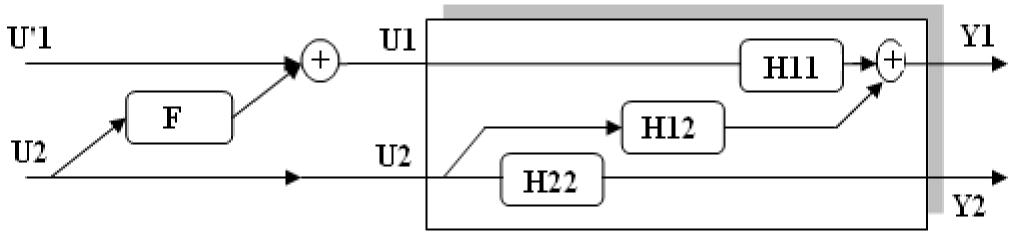

Figure 7: Decoupled system

where *F* represent the ideal decoupler.

To eliminate the interaction between U_2 and Y_1, after some simple mathematical manipulations, the expression for the ideal decoupler is given by the following expression [1-2]:

$$F(s) = \frac{-H_{12}(s)}{H_{11}(s)} \qquad (12)$$

In this paper, the partial static decoupler is used to decoupling the two aerothermic process loops [1-2]. The design equations for the decoupler can be adjusted by setting (s = 0), i.e. the process transfer functions are simply replaced by their corresponding steady state gains. Hence, the expression for the ideal decoupler given by the equation 3 becomes:

$$F = -\frac{H_{12}(0)}{H_{11}(0)} = 0.5850$$

In this paper, the decentralized PI-D controller is considered to reject the interaction effect between the temperature and the air flow. Its transfer function in the Laplace domain is given by the following equation [23]:

$$U(s) = K_c\left(1 + \frac{1}{\tau_i s} + \frac{w_d \tau_d s}{1 + \alpha \tau_d s}\right)E(s) + \frac{K_c \tau_d s}{1 + \alpha \tau_d s}(w_d - 1)Y(s) \qquad (13)$$

where *U(s)* is the manipulated variable, *Y(s)* is the output variable and *E(s)* the error signal. Parameters *Kc*, τ_i, and τ_d represent proportional gain, integral gain and derivative gain respectively. w_d is the parameter who can prevent the "derivative kick", which happens when a step set-point change enters.

With w_d =1, the equation 4 represents the conventional PID controller given by the following equation:

$$U(s) = K_c(1 + \frac{1}{\tau_i s} + \frac{\tau_d s}{1 + \alpha\tau_d s})E(s) \qquad (14)$$

But with w_d =0, the equation 14 is transformed to a PI-D controller given by the following equation:

$$U(s) = K_c(1 + \frac{1}{\tau_i s})E(s) - \frac{K_c \tau_d s}{1 + \alpha\tau_d s}Y(s) \qquad (15)$$

As shown by the equation 15, the derivative action does not directly operate on reference changes. But, it is entirely applied to the process output; which represents the newness of the traditional PID controller restructuring.

To calculate the PI and PI-D parameters, the Internal Model Control (IMC) tuning rules is adopted [23]. It is used most frequently in industrial processes because of its many advantages, including simplicity, robust performance, and its analytical form which is easier to implement in real time. The PI-D controller parameters are given by the table 1:

Table 1: IMC tuning rule

controller	Tuning parameters			
	Kc	τ_i	τ_d	λ
PI	$\frac{2\tau + \theta}{2K\lambda}$	$\tau + \frac{\theta}{2}$	-	$\geq 1.7L$
PI-D	$\frac{2\tau + \theta}{2K(\lambda + \theta)}$	$\tau + \frac{\theta}{2}$	$\frac{\tau\theta}{2\tau + \theta}$	$\geq 0.25L$

where K represents the steady-state gain, τ is the time constant, and θ is the time delay of the system.

V. EXPERIMENTAL RESULTS

The setup of the two controllers described in the previous section was first tested in simulation using the model obtained from identification. This investigation was done especially to evaluate the computational complexity of the two controllers and to find for each of them the tuning parameters before its implementation in the real aerothermic process.

For the CDSSMPC, the scaling factor and the number of terms used in the Laguerre functions are chosen respectively to be $a=[0.5\ 0.5]$ and $N=[2\ 2]$; Both scaling factors are selected to be approximately on the same orders of the open-loop dominant poles of the aerothermic process. The prediction horizon parameter is chosen to be $Tp=50$; and the weighting matrices Q and R are chosen respectively to be $Q=C^TC$ and $R=I_{2x2}$. The observer is given by the following result

$$K_{obs} = \begin{bmatrix} 0.7652 & 0 \\ 0.0728 & 0 \\ -0.5064 & 0 \\ 0 & -0.1295 \\ 0 & 0.1957 \\ 1.0507 & 0 \\ 0 & 1.1450 \end{bmatrix}$$

For the DPI-D controller, the following table summarizes the turning parameters for the first and the second loop [ramzi2].

Table 2: parameters of the PI-D and PI controllers using IMC tuning rules

controller	Tuning parameters			
	Kc	τ_i	τ_d	λ
PI	*1.0428*	*1.9302*	-	2
PI-D	*1.0804*	*37.5716*	*3.1740*	2

The implementation of the CDSSMPC, the conventional PID and the DPI-D controllers, in real time, use the Humusoft MF624 Data Acquisition Card of *14*-bit Analog to Digital (A/D) conversion module, plugged into ISA port. The signals are transmitted between the PC and the Aerothermic Process via a *37*-way cable and connector block. The robustness of the two controllers is evaluated by changing the set-point of the ventilator speed at time 200 second and 400 second.

Three experiences are then envisaged in order to challenge the performances of the Decentralized PI-D controller, the Centralized DSSMPC and the conventional ones. In the first and the second experience, the PI controller is used to regulate the air flow since this loop has generally very fast dynamics and its measurement is inherently noisy; while, the air temperature is regulated respectively by the DPI-D and the conventional PID controllers. In the third experience, the two aerothermic process loops are simultaneously controlled by the Centralized DSSMPC controller.

Figures 8, 9 and 10 represent respectively the aerothermic process controlled by the Decentralized PI-D and PI techniques, the conventional PID and the Centralized DSSMPC techniques. In all these figures, (Y_1,Y_2) represent the measured outputs or controlled variables, (U_1,U_2) represent the manipulated inputs and (R_1,R_2) represent the set-points. As shown in this figure 8, three controllers are used in the DPI-D controller: the PI-D controller, the conventional PI controller and the decoupler noted by *F*. noting that the input-signal to the decoupler, which is designed to compensate the undesirable process interactions, is the output signal from the feedback conventional PI controller.

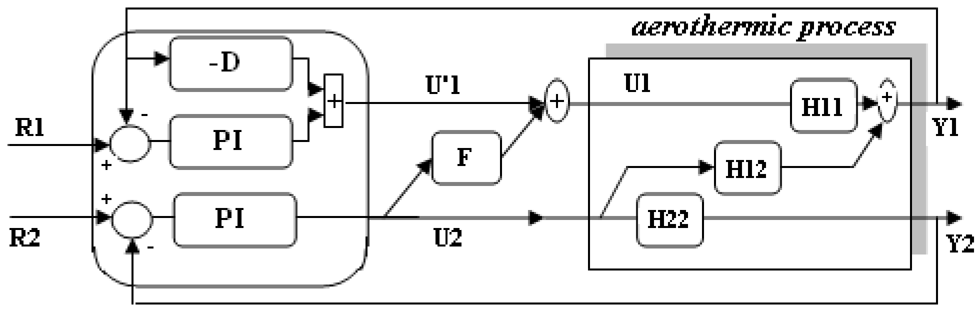

Figure 8. Block diagram of decentralized PI-D applications

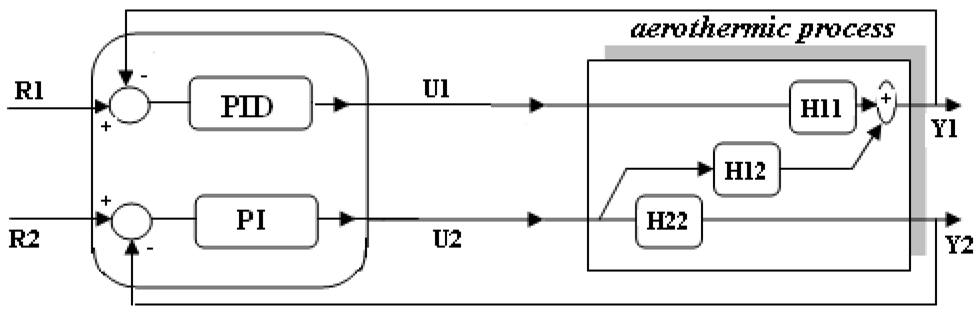

Figure 9. Block diagram of conventional PID applications

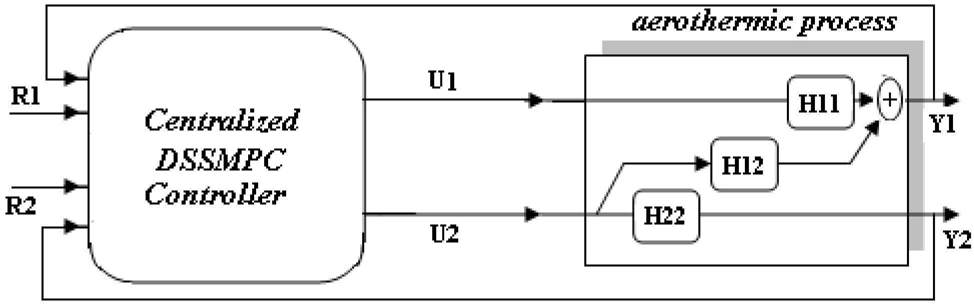

Figure 10. Block diagram of CDSSMPC applications

Figures 11 and 12 present the results of the three control techniques. It is apparent from these figures that the decentralized PI-D controller provides a good performance. The robustness and the effectiveness of the decentralized PI-D controller are confirmed by the elimination of the interaction effect on the air temperature variable compared to the conventional PID and the Centralized DSSMPC controllers. It is obvious that the decentralized controller affords a good robust performance consistently of this kind of process.

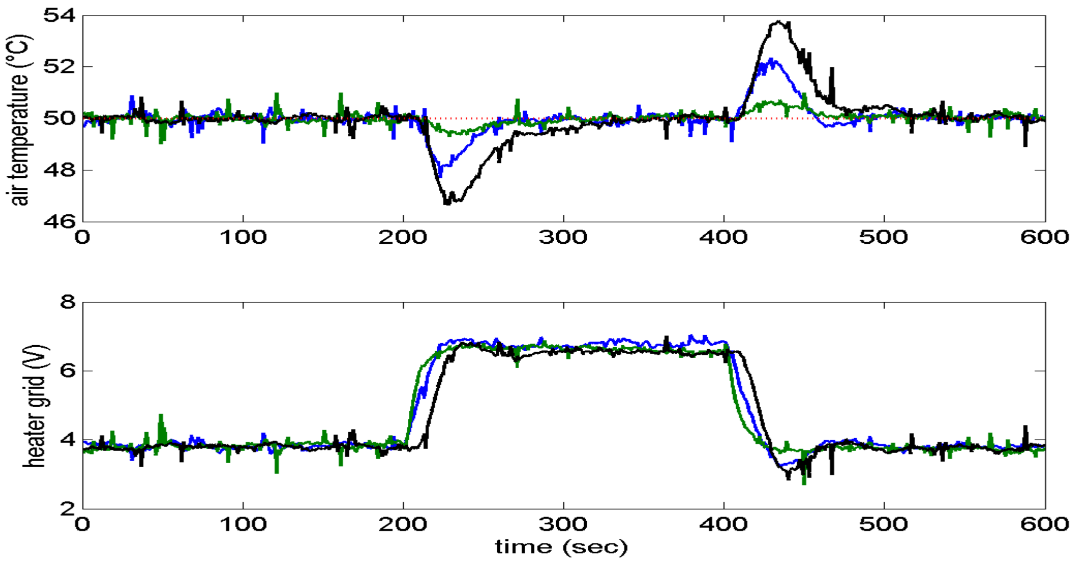

Figure 11: Top figure: closed-loop air temperature response; bottom figure: Closed-loop heater grid control response. (red: set point, green: Decentralized PI-D controller, blue: Centralized DSSMPC controller, black: conventional PID controller).

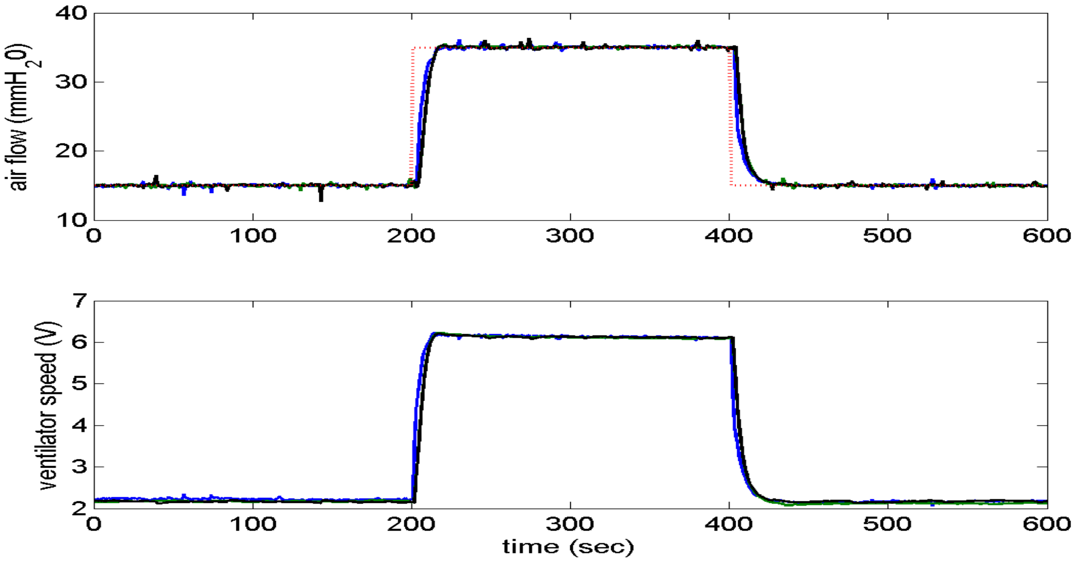

Figure 12: Top figure: closed-loop air flow response; bottom figure: Closed-loop ventilator speed control response (red: set point, green: PI controller, blue: Centralized DSSMPC controller, black: conventional PID controller).

VI. CONCLUSIONS

In this paper we have described both a Centralized Discrete State Space Model Predictive Control design approach and Decentralized PI-D controller for a pilot scale aerothermic process. The Continuous time State Space Identification is used to identify the basic model of the two approaches. For the CDSSMPC controller, an observer based on the Kalman filter is used to estimate the aerothermic process state variable. The design of this approach is based on the Laguerre functions. The design of DPI-D controller is based on the combination of the conventional PI-D controller and the static decoupler approach. The control systems are implemented using the Humusoft MF624 Data Acquisition Card of *14*-bit Analog to Digital (A/D) conversion module, plugged into ISA port.

Experimental results demonstrate robust performance of the Decentralized PI-D controller compared to the Centralized DSSMPC and the conventional PID ones for tracking set point changes and rejecting interactions effect. The DPI-D controller constitutes a worth extension of the mono-variable control methods and an alternative to the basic classical control for the system with lower level such as the aerothermic process.

REFERENCES

[1] M. Ramzi, N. Bennis, H. Youlal and M. Haloua, "Decentralized PI-D Controller applied to an Aerothermic Process", *International journal on smart sensing and intelligent systems*, vol. 5, no. 4, 2012, pp. 1003-1018.

[2] M. Ramzi, H. Youlal and M. Haloua, "Continuous Time Identification and Decentralized PID Controller of an Aerothermic Process", *International journal on smart sensing and intelligent systems*, vol. 5, no. 2, 2012, pp. 487-503.

[3] N. Bennis, M. Ramzi, H. Youlal and M. Haloua, "LMI solutions for H_2 and H_∞ decentralized controllers applied to an Aerothermic Process", *J Control Theory Appl,* Vol. 11, No. 2, 2013, pp. 141–148.

[4] M. Ramzi, H. Youlal and M. Haloua, "State Space Model Predictive Control of an Aerothermic Process with Actuators Constraints," *Intelligent Control and Automation*, Vol. 3 No. 1, 2012, pp. 50-58.

[5] N. Bennis, J. Duplaix, G. Enéa, M. Haloua, H. Youlal, "Greenhouse climate modelling and robust control", *Computers and Electronics in Agriculture*, Vol. 61, 2008, pp. 96-107.

[6] M.F. Rahmat, N.A. Mohd Subha, Kashif M.Ishaq, N. Abdul Wahab, "Modeling and controller design for the VVS-400 pilot scale heating and ventillation system", *International journal on smart sensing and intelligent systems*, Vol. 2, No. 4, 2009, pp. 579-601.

[7] Yong Xiao, Chi Zhang, Xiaoyu Ge, Peiqi Pan, "Feedforward control of temperature-induced head skew for hard disk drives", *International journal on smart sensing and intelligent systems,* Vol. 5, no. 1, 2012, pp. 95-105.

[8] Mohd Fua'ad Rahmat, Amir Mehdi Yazdani, Mohammad Ahmadi Movahed, Somaiyeh Mahmoudzadeh, "Temperature control of a continuous stirred tank reactor by means of two different intelligent strategies", *International journal on smart sensing and intelligent systems,* Vol. 4, no. 2, 2011, pp. 244-267.

[9] Aman Tyagi, Arrabothu Apoorv Reddy, Jasmeet Singh, Shubhajit Roy Chowdhury, "low cost portable temperature-moisture sensing unit with artificial neural network based signal conditioning for smart irrigation applications", *International journal on smart sensing and intelligent systems,* Vol. 4, no. 1, 2011, pp. 94-111.

[10] J. Y. Chang, "Thermal analysis and design of disk-spindle radial repeatable runout in spinning data storage devices," *IEEE Transactions on Magnetics*, vol. 47, no. 7, 2011, pp. 1855-1861.

[11] T. Kealy, A. O'Dwyer, "Closed Loop Identification of a First Order plus Dead Time Process Model under PI Control", *Proceedings of the Irish Signals and Systems Conference, University College*, Cork, 2002, pp. 9-14.

[12] D.M. de la Pena, D.R. Ramirez, E.F. Camacho, T. Alamo, "Application of an explicit min-max MPC to a scaled laboratory process", *Control Eng. Practice*, Vol. 13, No. 12, 2005, pp. 1463-1471.

[13] E. Yesil, M.Guzelkaya, I.Eksin, O. A. Tekin, "Online Tuning of Set-point Regulator with a Blending Mechanism Using PI Controller". *Turk J Elec Engin*, 2008, Vol.16, No. 2, pp. 143-157

[14] R. Mooney and A. O'Dwyer, "A case study in modeling and process control: the control of a pilot scale heating and ventilation system", *Proceedings of IMC-23; the 23rd International Manufacturing Conference, University of Ulster, Jordanstown*, August, 2006, pp. 123-130.

[15] Manual for ERD004000 Flow and Temperature process, 78990 ELANCOURT, FRANCE, 2008.

[16] L. P. Wang, "Model Predictive Control System design and Implementation Using MATLAB" *Springer, Berlin*, 2009.

[17] H. Garnier, M. Gilson, T. Bastogne, and M. Mensler, "CONTSID toolbox: a software support for continuous-time data-based modelling. In Identification of continuous time models from sampled data", *H.Garnier and L. Wang (Eds.), Springer, London*, 2008, pp. 249-290.

[18] S.C.Mukhopadhyay, T.Ohji, M.Iwahara and S.Yamada, "Design, Analysis and Control of a New Repulsive Type Magnetic Bearing", IEE proceeding on Electric Power Applications, vol. 146, no. 1, pp. 33-40, January 1999.

[19] H. Garnier, L. Wang, and P.C. Young, "Direct Identification of Continuous-time Models from Sampled Data: Issues, Basic Solutions and Relevance in Identification of continuous-time models from sampled data", *Springer*, London, 2008, pp. 1-29.

[20] S.C.Mukhopadhyay, T.Ohji, M.Iwahara and S.Yamada, "Modeling and Control of a New Horizontal Shaft Hybrid Type Magnetic Bearing", IEEE Transactions on Industrial Electronics, Vol. 47, No. 1, pp. 100-108, February 2000.

[21] Hugues Garnier, "Data-based continuous-time modelling of dynamic systems", *4th International Symposium on Advanced Control of Industrial Processes*, Adconip China 2011, pp. 146-153.

[22] G. Sen Gupta, S.C.Mukhopadhyay, S. Demidenko and C.H.Messom, "Master-slave Control of a Teleoperated Anthropomorphic Robotic Arm with Gripping Force Sensing", IEEE Transactions on Instrumentation and Measurement, Vol. 55, No. 6, pp. 2136-2145, December 2006.

[23] V. Laurain, M. Gilson, R. Toth, H. Garnier, "Direct identification of continuous-time LPV models", *American Control Conference*, 2011, pp. 159-164

[24] I-Lung Chien, Hsiao-Ping Huang, Jen-Chien Yang, "A Simple multiloop tuning method for PID controllers with no proportional kick", *Ind. Eng. Chem. Res.*, Vol. 38, 1999, pp. 1456-1468.

[25] Dale E. Seborg, Thomas F. Edgard, Duncan A. Mellichamp, "Process dynamics and control", Second edition, John Wiley & sons, 2004 , pp. 473-502

[26] Su Whan Sung, Jietae Lee, In-Beum Lee, "process identification and PID control", *John Wiley & Sons (Asia)*, 2009.